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Title: Petrology and physics of magma ocean crystallization

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Summary of problem and research effort

Early Mars is thought to have been melted significantly by the conversion of kinetic energy to heat during accretion of planetesimals (*e.g.*, Kaula, 1979; Hess, 2002). The processes of solidification of a magma ocean determine initial planetary compositional differentiation and the stability of the resulting mantle density profile. The stability and compositional heterogeneity of the mantle have significance for magmatic source regions, convective instability, and magnetic field generation. Significant progress on the dynamical problem of magma ocean crystallization has been made by a number of workers (*e.g.*, Tonks and Melosh, 1990; Franck, 1992; Morse, 1993; Abe, 1997; Solomatov, 2000).

The work done under the 2003 MFRP grant further explored the implications of early physical processes on compositional heterogeneity in Mars. Our goals were to connect early physical processes in Mars' evolution with the present planet's most ancient observable characteristics, including the early, strong magnetic field, the crustal dichotomy, and the compositional characteristics of the SNC meteorite's source regions as well as their formation as isotopically distinct compositions early in Mars's evolution. We had already established a possible relationship between the major element compositions of SNC meteorite sources and processes of Martian magma ocean crystallization and overturn, and under this grant extended the analysis to the crucial trace element and isotopic SNC signatures. This study then demonstrated the ability to create and end the magnetic field through magma ocean cumulate overturn and subsequent cooling, as well as the feasibility of creating a compositionally- and volumetrically-consistent crustal dichotomy through mode-1 overturn and simultaneous adiabatic melting.

Likelihood of a magma ocean on Mars

The conversion of kinetic energy to heat during accretion of a Mars-sized planet may produce heating of 1,500°C (*e.g.* Wetherill, 1990; Senshu *et al.*, 2002). The potential energy release of core formation in the terrestrial planets is expected to raise the temperature of the planetary interior by an additional 300°C (Solomon, 1979). The sum of these processes clearly can melt the entire silicate mantle of a planet if they happen quickly enough to avoid losing heat to space, or if they happen in the presence of an insulating atmosphere (Abe, 1993, 1997).

Over the last decade estimates for the time of differentiation of the terrestrial planets have been made using ^{182}W and ^{142}Nd anomalies that date the fractionation of the core and mantle. The estimated period for core and mantle fractionation has shortened from within 10 to 13 Myr of the origin of the solar system (Blichert-Toft *et al.*, 1999; Lee and Halliday, 1995; Shih *et al.*, 1999; Kleine *et al.*, 2002; Yin *et al.*, 2002) to less than 5 Myr after solar system formation (Stein Jacobsen and Alex Halliday, personal communications). Accretion and core formation of a speed that allows mantle differentiation before 5 Myr have passed would produce significant and perhaps complete melting of the large terrestrial planets (*e.g.*, Wood *et al.*, 1970; Smith *et al.*, 1970; Solomon, 1979; Stevenson, 1987; Wetherill, 1990; Halliday *et al.*, 2001; McSween, 1994; Hess and Parmentier, 2001).

Summary of work completed

Given the high likelihood of a magma ocean on early Mars, the processes of solidification of the magma ocean determine initial planetary compositional differentiation. We have developed a Matlab-based model for magma ocean crystallization that produces density, temperature, and compositional profiles for a fractionally crystallized magma ocean. The model calculates accurate densities for mineral assemblages based on phase composition, temperature, and pressure.

We have made significant progress in addressing the following magma ocean processes:

- 1) major and trace element heterogeneities in the Martian mantle created during crystallization,
- 2) crystal settling and segregation of crystals of different densities in the liquid and partially liquid magma ocean zones,
- 3) melt migration processes and trapped melt fractions in solidifying magma ocean cumulates,
- 4) production of an early magnetic field through high core heat flux created by solid-state cumulate overturn following magma ocean crystallization, and
- 5) creation of an early crust on Mars by adiabatic melting during solid-state cumulate overturn.

Our models now incorporate interstitial melt and trace element partitioning, and we can calculate the Sm/Nd and Lu/Hf ratios and initial isotopic compositions for each layer of the crystallizing magma ocean, and thus for each portion that melts during overturn to create crust. We can also predict the regions in Mars where the bulk of heat-producing elements should reside as a result of magma ocean processes. These enhancements mean that our models can now make testable predictions that relate to the current state of Mars.

Magma ocean crystallization produces an unstable cumulate density stratification primarily because of magnesium and iron exchange with the evolving magma ocean liquids. Overturn of the solid, unstable cumulates to a stable configuration is rapid and efficient (Solomatov, 2000; Elkins-Tanton *et al.*, 2003). During overturn, hot cumulates may rise from depth, decompress above their solidii and melt,

producing an early crust. No early stagnant lid is likely to form before a significant crystal fraction reaches the surface of the planet, and so solid-state cumulate overturn following magma ocean crystallization is the likeliest process to produce the earliest crust of Mars.

Aspects of Martian evolution that our models may explain

1) Formation of isotopically distinct magmatic source regions in the first few million years of Martian evolution. The extreme ϵ^{Nd} values and presence of ^{142}Nd anomalies indicate the SNC meteorite source reservoirs differentiated very early in Mars history, and have remained separate (Jones, 1986; Harper *et al.*, 1995; Borg *et al.*, 1997). Brandon *et al.* (2000) has also correlated the ^{182}W and ^{142}Nd anomalies with Re-Os systematics, arguing that the isotopic composition of the Martian meteorites was set in the earliest differentiation history of Mars.

2) Formation of source regions for the SNC meteorites that are consistent with the major and trace element compositions inferred from the meteorites themselves. The SNC meteorite compositions indicate an iron-rich, alumina-poor source, compared to the Earth's mantle (Longhi *et al.*, 1992) or chondritic meteorites. Isotopic characteristics indicate that the nakhlites and Chassigny came from an incompatible-element depleted source, and that EETA, Los Angeles, Zagami, and Shergotty all came from an incompatible-element enriched source (Blichert-Toft *et al.*, 1999; Herd *et al.*, 2002). Our models produce shallow source regions consistent with the inferred SNC source regions.

3) Creation of two distinct compositions of early basaltic crust via adiabatic melting of rising mantle materials during solid-state cumulate overturn. The oldest regions of crust in both the southern highlands and the northern lowlands appear to date to the Noachian. The preservation of whole-rock Rb-Sr isochrons and ^{182}W and ^{142}Nd anomalies are also evidence that there has been little or no crustal recycling since magma ocean solidification (Hess, 2002; Blichert-Toft *et al.*, 1999). Adiabatic melting during overturn in our models produces two compositions of early crust roughly consistent with remote sensing results from Mars.

4) Production of a strong, brief, early magnetic field by a core dynamo created by cold cumulates falling against the core-mantle boundary during solid-state cumulate overturn. Magnetized crustal provinces, mainly in the southern hemisphere, are evidence for very ancient crustal formation, perhaps within the first few hundred million years after accretion (*e.g.* Acuña *et al.*, 1999; Purucker *et al.*, 2000). Cold cumulates fall to the core-mantle boundary during cumulate overturn and produce a high heat flux from the core. One-dimensional solutions to the conductive heat equation show that the resulting core heat flux is sufficient to drive a dynamo for between 25 and ~150 Myr.

5) Establishment of a mantle with a stable compositional profile that inhibits thermal convection, maintaining the compositional heterogeneities created by initial magma ocean

crystallization. The isotope characteristics of the SNC meteorites were produced in the earliest few hundred million years of planetary development, and these source regions were not mixed to homogeneity over the age of the solar system, since some SNC meteorites date almost to the present day. The stability of magma ocean cumulates following overturn gives a simple mechanism for suppressing violent convection and maintaining the separation of source heterogeneities.

Summary of presentations, abstracts, talks, and publications

One paper has been published and a second is in revision:

Elkins-Tanton L.T., E.M. Parmentier, P.C. Hess (2003) Magma ocean fractional crystallization and cumulate overturn in terrestrial planets: Implications for Mars. *Meteoritics and Planetary Science* 38, 1753-1771.

Elkins-Tanton L.T., S. Zaranek, and E.M. Parmentier (2005) Early Martian magnetic field as a result of magma ocean cumulate overturn, in revision for *Earth and Planetary Science Letters*.

The results have been presented at a number of scientific conferences:

Parmentier, E.M. and L.T. Elkins-Tanton, Convection and layering in the Martian mantle, Unmixing the SNCs: Chemical, Isotopic, and Petrologic Components of the Martian Meteorites, workshop at the Lunar and Planetary Science Institute, Houston TX, October 2002.

Elkins-Tanton L.T., E.M. Parmentier, P.C. Hess, A model for Martian magma ocean crystallization and overturn, Lunar and Planetary Science Conference XXXIII Abstracts, 2003.

Elkins-Tanton L.T., E.M. Parmentier, P.C. Hess, A model for Martian magma ocean crystallization and overturn, EGS/AGU/EUG combined meeting abstracts, Spring 2003. INVITED.

Zaranek S.E., E.M. Parmentier, and L.T. Elkins-Tanton, Overturn of unstably stratified, inhomogeneous fluids: Implications for the early evolution of planetary mantles, Lunar and Planetary Science Conference XXXV Abstracts, March 2004.

Zaranek S.E., Elkins-Tanton L.T., Parmentier E.M., Role of Compositional Stratification on the Evolution of Planets, Computer Measurement Group Conference 2004, Courant Institute of Mathematical Sciences, New York, June 2004.

Elkins-Tanton L.T., S.E. Zaranek, and E.M. Parmentier, Martian early magnetic field as a result of magma ocean cumulate overturn, Workshop on Hemispheres apart: the origin and modification of the Martian crustal dichotomy, Houston TX, October 2004.

Elkins-Tanton L.T., S.E. Zaranek, and E.M. Parmentier, Martian early crust as a result of magma ocean cumulate overturn, Workshop on Hemispheres apart: the origin and modification of the Martian crustal dichotomy, Houston TX, October 2004.

Elkins-Tanton L.T., S.E. Zaranek, and E.M. Parmentier, Magma ocean cumulate overturn: Generation of an early magnetic field, Second Conference on Early Mars: Geologic, hydrologic, and climatic evolution and implications for life, Jackson Hole WY, October 2004.

Elkins-Tanton L.T., S.E. Zaranek, and E.M. Parmentier, Magma ocean cumulate overturn: Generation of an early crust, Second Conference on Early Mars: Geologic, hydrologic, and climatic evolution and implications for life, Jackson Hole WY, October 2004.

Zaranek S., L.T. Elkins-Tanton, E. Parmentier, Magma Ocean Overturn: Implications for The Creation of Large Scale Mantle Heterogeneities and Influences on Planetary Evolution, American Geophysical Union Abstracts, Fall Meeting, 2004.

Elkins-Tanton L.T. and E. M. Parmentier, The fate of water in the Martian magma ocean and the formation of an early atmosphere, Lunar and Planetary Science Conference XXXVI Abstracts, March, 2005.

This research has also been presented in invited talks:

Princeton University (November 2003)

Rice University (March 2004)

Carnegie Institute of Washington, Department of Terrestrial Magnetism (March 2004)

Harvard University (September 2004)

Massachusetts Institute of Technology (February 2005)

California Institute of Technology (February 2005).

Significant additional questions

We will propose addressing the following questions in our next MFRP proposal:

- 1) Can the patterns of cumulate overturn produce melting in a pattern consistent with the crustal dichotomy?
- 2) Can crystallization of a wet magma ocean produce a wet mantle, and what are the consequences for later convection and magma production?
- 3) What effects would a partial magma ocean have on the resulting Martian mantle?

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